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14. ABSTRACT
Research which was conducted prior to the development of the present titanium armor alloy (Ti-6Al-4V) is discussed briefly. More recent ballistic evaluations on a variety of commercially available titanium alloys are presented and compared to the 6Al-4V alloy. The effects of chemical analysis, mechanical properties, heat treatment, and microstructure on the ballistic performance of the present titanium armor alloy are discussed in respect to the newly developed titanium armor specification. Current research on deformation processing of the Ti-6Al-4V alloy in respect to mechanical properties and ballistic improvements is discussed. Areas of future research on deformation processing and solidification to eliminate spalling both under fragment-simulating and large armor-piercing attack are indicated.

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AMSRL-WT-TA (70) 2 November 1995

MEMORANDUM FOR Director, U.S. Army Research Laboratory, ATTN: AMSRL-MA-C, (R. Adler), Aberdeen Proving Grounds, MD, 21005-5066

SUBJECT: Distribution Marking of Document

1. This office has received a request for a copy of a reference in an Armor Mechanics Branch paper presented at a recent conference. The reference was a paper given and published in the "Proceedings of the Metallurgical Advisory Committee on Rolled Armor", AMRA MS 64-06, published in January 1964. The paper is found on pages 195-228 and is entitled "Status and Potential of Titanium Armor" by Joseph Sliney; a copy is attached. The overall report was originally classified Confidential, but was declassified on 1 March 1994 per the Security Guide on Armor Materials, dated 30 July 1993. The Sliney paper itself was unclassified in 1964, but was then and is still now controlled by the distribution marking.

2. As the current originating office of this work, your approval is requested on removal of the control marking and allowing the paper to become Distribution A, Approved for Public Release. Sliney's work represents a historical document on the early ballistic work on titanium and merits a wider distribution and acknowledgement. Earlier work by Pitler and Hurlich, Watertown Arsenal report #401/17, March 1950 and later reports by Riffin, Corrigan and Mascianica and others document a period of work not fully appreciated today and only recently being revisited. A review of the Sliney document by this office does not warrant any control markings on the paper. The Security Office recommends the "easiest" solution is to prepare an ARL-1 which provides the required OPSEC and technical review. I have enclosed the filled out form which requires three signatures and the OPSEC reviewer signature. I assume Martin Wells would be the technical reviewer, as this office has had many previous contacts with him on current titanium issues. To speed the process, this office will obtain the public Affairs signature after your review since they are close by.

3. This office would like to clear this correspondence from our records and requests your review as quick as possible. Your assistance in this matter is appreciated. The point of contact is William A. Gooch, (410) 278-6080.

FOR THE DIRECTOR:

Enclosure

THOMAS A. HAVEL
Section Leader, Reactive and
Composite Armor

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A. General information

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3. Author(s): Joseph Sliney (Requestor - W. A. Gooch)
SLINEY

4. Office symbol or affiliation: AMSRL-WT-TA

5. Telephone: 278-6080

6. Contractor generated? ☒ no ☐ yes ______
(If yes, enter your contract No. and ARL POC)

7. Type ☒ Report ☐ External publication ☐ Presentation (speech, briefing, slides, etc.)

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20. Is publication a refereed journal? ☐ no ☐ yes

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All information (for external dissemination/presentation)

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R H Adler 7 Nov 95
(date)

29. Technical reviewer/panel chairman
W Gooch Wells 7 NOV 95
(date)

30. Editorial reviewer
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RBD Adler 7 Nov 95

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Space for explanations/continuations from reverse

Paper - "Status and Potential of Titanium Armor".

This ARL-1 is for removing control markings on pages 195 - 228 for Distribution A Release.

Document was declassified on 1 March 1994 per SCG for Armor Materials, 30 July 1993.

SESSION III

NONFERROUS ARMOR DEVELOPMENTS

Chairman: Mr. Francis S. Mascianica,
U.S. Army Materials Research Agency

STATUS AND POTENTIAL OF TITANIUM ARMOR

by

MR. JOSEPH L. SLINEY
U.S. Army Materials Research Agency
Watertown, Massachusetts

ABSTRACT (U)

(U) Research which was conducted prior to the development of the present titanium armor alloy (Ti-6Al-4V) is discussed briefly. More recent ballistic evaluations on a variety of commercially available titanium alloys are presented and compared to the 6Al-4V alloy. The effects of chemical analysis, mechanical properties, heat treatment, and microstructure on the ballistic performance of the present titanium armor alloy are discussed in respect to the newly developed titanium armor specification. Current research on deformation processing of the Ti-6Al-4V alloy in respect to mechanical properties and ballistic improvements is discussed. Areas of future research on deformation processing and solidification to eliminate spalling both under fragment-simulating and large armor-piercing attack are indicated.

INTRODUCTION (U)

(U) Between the years 1946 and 1956, the U.S. Army Materials Research Agency (AMRA) in cooperation with industry evaluated some eighty or more titanium alloys for armor. Most of these alloys were of poor ballistic quality because of the inferior melting stock, melting practice, and processing procedures used during the infancy of the titanium industry. Often, high-hardness titanium sponge having high percentage of interstitial elements (carbon, oxygen, hydrogen, nitrogen) was used for the melt. As a result of alloy development studies,[1] it was realized that in order to

obtain an optimum combination of strength and toughness the maximum hardness of the sponge had to be limited to approximately 140 Brinell. In addition to the sponge problem, early melting practices involved the use of graphite molds from which the melt absorbed high percentages of carbon. This deficiency was overcome by the use of water-cooled copper crucibles and the consumable electrode vacuum-melting practice as it is used today. These early processing practices, which resulted in high interstitial levels, obscured the important mechanical and metallurgical variables which are important for high ballistic quality armor.

(U) The 4 percent chromium — 2 percent molybdenum titanium alloy and the 7 percent manganese titanium alloy (RC 130AW) are two of the early titanium alloys which were developed for armor. The 7Mn alloy was ballistically superior to the 4Cr-2Mo alloy against armor-piercing (AP) ammunitions. This was attributed to the higher yield and ultimate tensile strengths of the 7Mn titanium alloy.[2]

(U) The first titanium prototype armored vehicle was fabricated from the 7Mn alloy by the use of unalloyed filler wire.[3] This was a utility vehicle named the ONTOS. Further vehicle prototype work has been discouraged by high material and fabrication costs of titanium.

(U) The present titanium armor alloy (Ti-6Al-4V) was developed at the Armour Research Foundation under the sponsorship of AMRA during the period 1954 to 1955.[4] This titanium alloy has been found to offer considerably more ballistic protection against fragment-type ammunition than the 7 percent Mn alloy.[2]

(U) Since 1958, AMRA has evaluated many of the commercial and semi-commercial titanium alloys in an effort to obtain ballistic improvements over the 6Al-4V alloy. These evaluations have consisted of ballistic and metallurgical tests on the various alloys which were tested in most cases in the annealed and solution-treated-plus-aged conditions at a thickness level of 5/8 inch. The alloys that have been evaluated are listed in Table I with the respective plate mechanical properties. Very little ballistic difference exists between various titanium alloys when evaluated with armor-piercing ammunition except for those alloys which are extremely brittle and fail by plate shattering or back-spalling. An example of a plate that back-spalled under caliber .30 AP M2 projectile attack is presented in Figure 1.

(U) In addition to the ballistic tests conducted at AMRA, Aberdeen Proving Ground has tested, in cooperation with the U.S. Army Tank-Automotive Center, heavy gage 6Al-4V plates of 1", 1-1/2", 2", 3", and 5" thickness levels with large AP projectiles.[5] The 5-inch-thick plate after attack by 90mm AP M318 projectiles is presented in Figure 2. The large back spalls should be noted.

(U) In addition to testing the various alloys mentioned above (Table I) with AP projectiles, the plates were also tested with soft, blunt-nose

TABLE I (U)

Commercial and Semi-Commerical Titanium Alloys Evaluated for Armor. (U)

Alloy	Condition	Yield Strength (ksi)	Tensile Strength (ksi)	Elon (%)	Reduction of area (%)	Density (lb/cu in)
Ti-5Al-2.5Sn	Annealed 1325 F, 4 hr; AC	120	125	20	36	0.161
Ti-8Al-2Cb-1Ta	Annealed 1650 F, 1 hr; AC	120	130	18	32	0.159
Ti-8Al-8Zr-1(Cb+Ta)	Annealed 1650 F, 1/2 hr; AC	125	130	5	8	0.160
Ti-6.5Al-2Cb-1Ta	Annealed	100	115	20	36	0.160
ALPHA-BETA ALLOYS Ti-4Al-4Mn	Annealed	135	137	17	28	0.163
Ti-4Al-3Mo-1V	Annealed Ht 1650 F, 2 hr; WQ 1200 F, 4 hr; AC	115 120	120 135	17 16	36 25	0.163
Ti-5Al-2.75Cr-1.25Fe (RS 140)	Annealed HT 1475 F, 2 hr; WQ 900 F, 5 hr; AC	135 165	155 190	15 7	30 10	0.163
Ti-5Al-1.5Fe-1.4Cr-1.2Mo	1650 F, 1 hr; WQ 1100 F, 2 hr; AC	160	170	12	30	0.160
Ti-6Al-4V	Annealed HT 1700 F, 1 hr; WQ 1100 F, 4 hr; AC	125 145	135 155	15 14	33 36	0.163
Ti-4Al-4V	Annealed HT 1650 F, 1/2 hr; WQ 1000 F, 1/4 hr; AC	110 135	115 140	17 12	45 38	0.161
Ti-6Al-6V-2.5Sn	Annealed HT 1630 F, 1/2 hr; WQ 1100 F, 4 hr; AC	155 185	160 190	15 9	32 26	0.163
BETA ALLOYS Ti-13V-11Cr-3Al	HT 1400 F, 1/2 hr; AC HT 1400 F, 1/2 hr; AC 900 F, 24 hr; AC	130 170	135 190	17 6	38 10	0.175

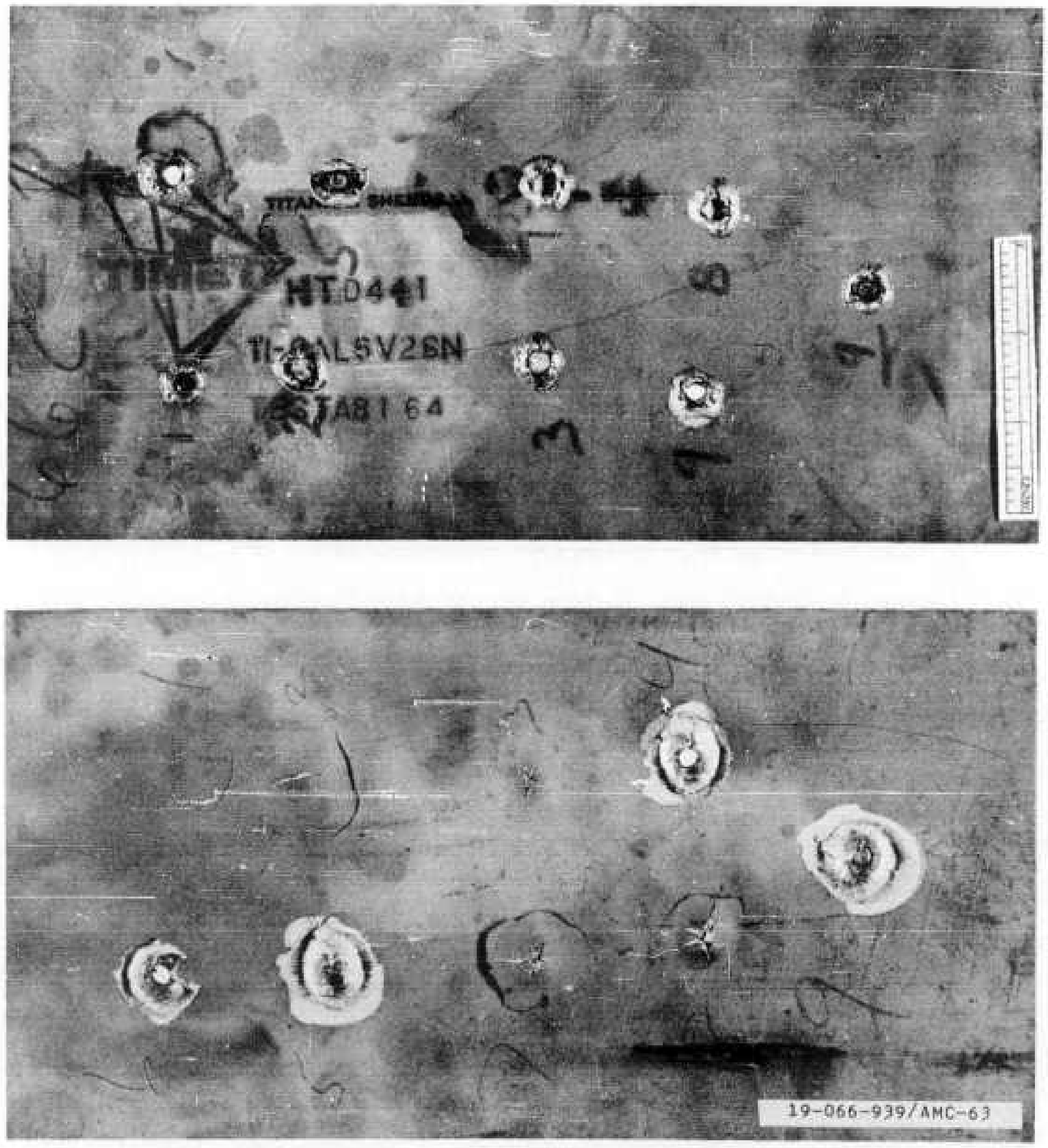


Figure 1 (U). TITANIUM ALLOY (6Al-6V-2.5Sn ANNEALED) AFTER BALLISTIC ATTACK WITH CAL. .30 AP M2 PROJECTILE AT 0° OBLIQUITY.(U)

Figure 2 (U). TITANIUM ALLOY (6A1-4V) ANNEALED) 5-INCH-THICK PLATE AFTER ATTACK BY 90MM AP M318 PROJECTILE.(U)

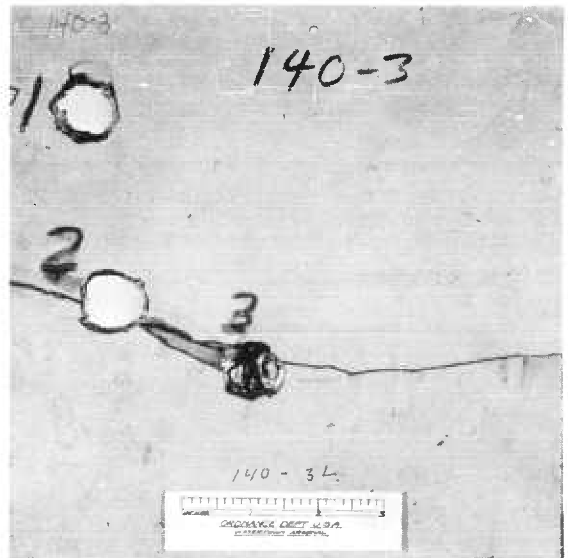
fragment simulators. These projectiles are representative of the type of fragments given off by the explosion of a 105mm H.E. shell. With this projectile, significant ballistic differences did exist among the various alloys. Those alloys which exhibited low ballistic performance failed either by plate shattering due to excessive plate brittleness, by back-spalling without the projectile penetrating the plate, or by a low-energy shear process which is associated with an acicular or transformed Widmanstatten microstructure. The low-energy shear mechanism of penetration will be described in detail later in this paper. Examples of plates which fail by shattering and back-spalling are presented in Figures 3 and 4. In comparison with the previous four figures, examples of the annealed 6Al-4V titanium armor when attacked by caliber .30 AP and caliber .50 fragment-simulating (FS) projectiles are presented in Figures 5 and 6. In Figure 5, the lack of back-spalling and cracking should be noted in comparison with Figure 2. When the annealed 6Al-4V titanium alloy is penetrated by the caliber .50 FS projectile, Figure 6, a complete penetration is characterized by bulging and some spalling on the back surface of the plate. The elimination of this type of spalling has been the subject of a great deal of research at AMRA and will be discussed further in this paper.

(U) At the present time,[6,7] the annealed Ti-6Al-4V has been found to be equal or superior to all of the other alloys tested. The 6Al-4V alloy provides a 25 to 30 percent weight savings when compared to steel armor for the same ballistic protection at areal densities of interest. Little hope exists at the present time for providing increased ballistic protection by strengthening through alloying or heat treating. Examples of the alloys tested with high percentages of alloying elements are the 6Al-6V-2.5Sn and the all-beta alloy. Both of these alloys were ballistically inferior in both the annealed and heat-treated conditions to the annealed 6Al-4V alloy. Two areas exist where improvements can be made to eliminate brittle failures (spalling and cracking) under ballistic attack, namely, solidification and deformation processing. Research in these areas should eventually permit the use of the higher strength titanium alloys and result in improved AP ballistic performance as well as fragment performance.

PRESENT STATUS OF TITANIUM ARMOR (U)

(U) Chemical variables that were not considered significant in the early titanium armor studies have proven to be extremely important. The interstitial elements — carbon, oxygen, hydrogen and nitrogen — in very small quantities, can cause severe embrittlement, not only resulting in spalling but also in poor low-temperature shock resistance and inferior weldability.

(U) At the present time, the lowest commercially produced carbon level is 0.040 to 0.020 weight percent maximum. Even at this low level, carbides which are stable up to very high temperatures are strung out during the rolling operation and have been associated with spall formation in the 6Al-4V alloy when attacked by fragment-type ammunition. An illustration



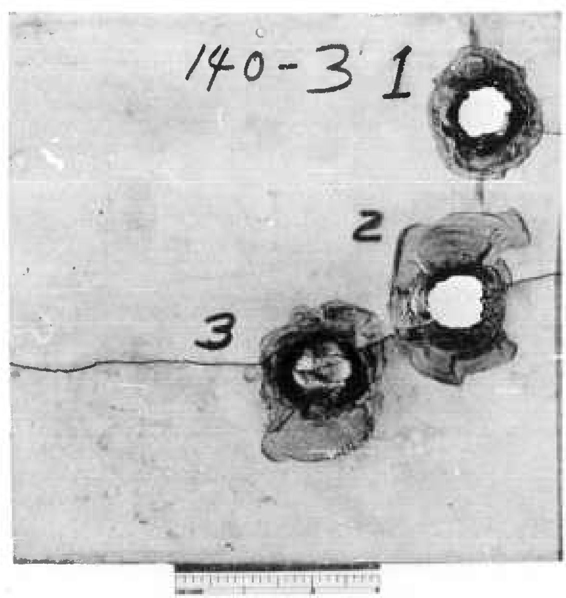


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Figure 3 (U). BALLISTIC TEST PLATE — HEAT-TREATED Ti-5Al-2.75Cr-1.25Fe (RS140) (YIELD STRENGTH 160 KSI) AFTER BALLISTIC ATTACK BY CAL. .50 FS PROJECTILE AT 0° OBLIQUITY.(U)

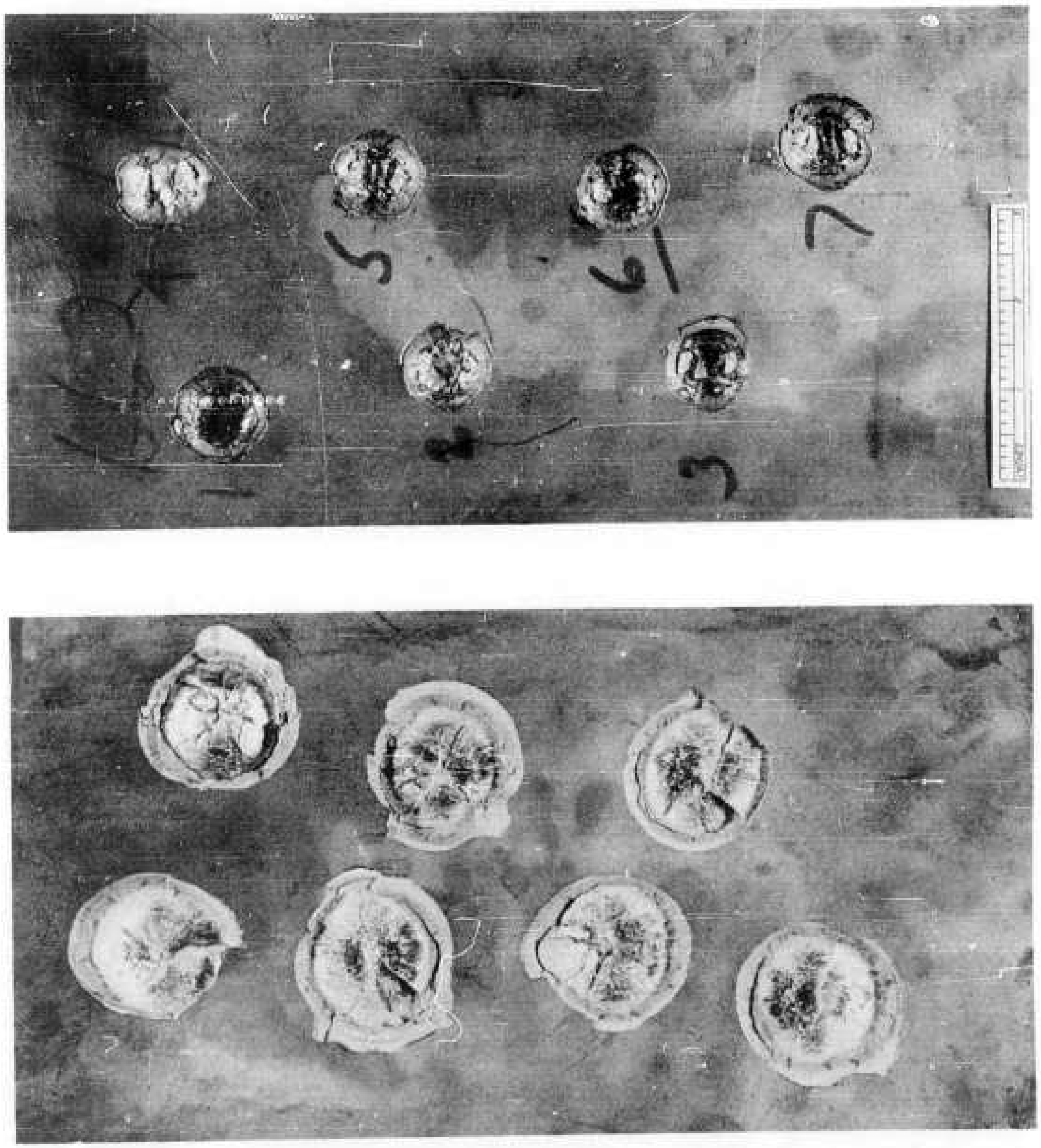

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Figure 4 (U). TITANIUM ALLOY (6Al-6V-2.5Sn ANNEALED) AFTER BALLISTIC ATTACK BY CAL. .50 FS PROJECTILE AT 0° OBLIQUITY. (U)

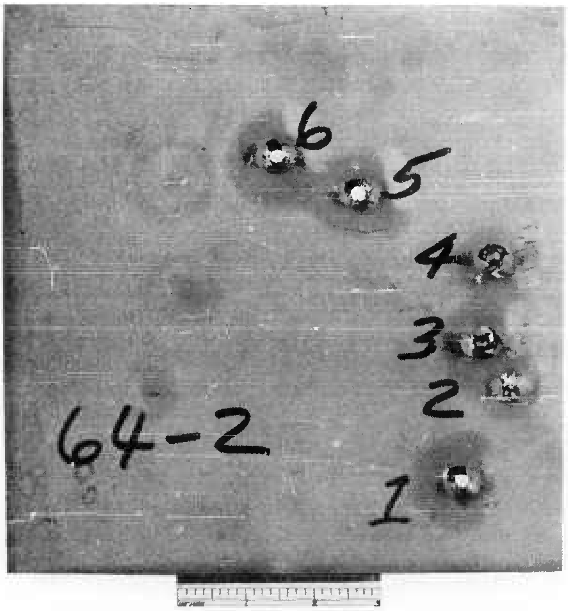

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Figure 5 (U). BALLISTIC TEST PLATE (Ti-6Al-4V ANNEALED, YIELD STRENGTH 125 KSI) AFTER BALLISTIC ATTACK BY CAL. .30 AP PROJECTILE AT 0° OBLIQUITY.(U)

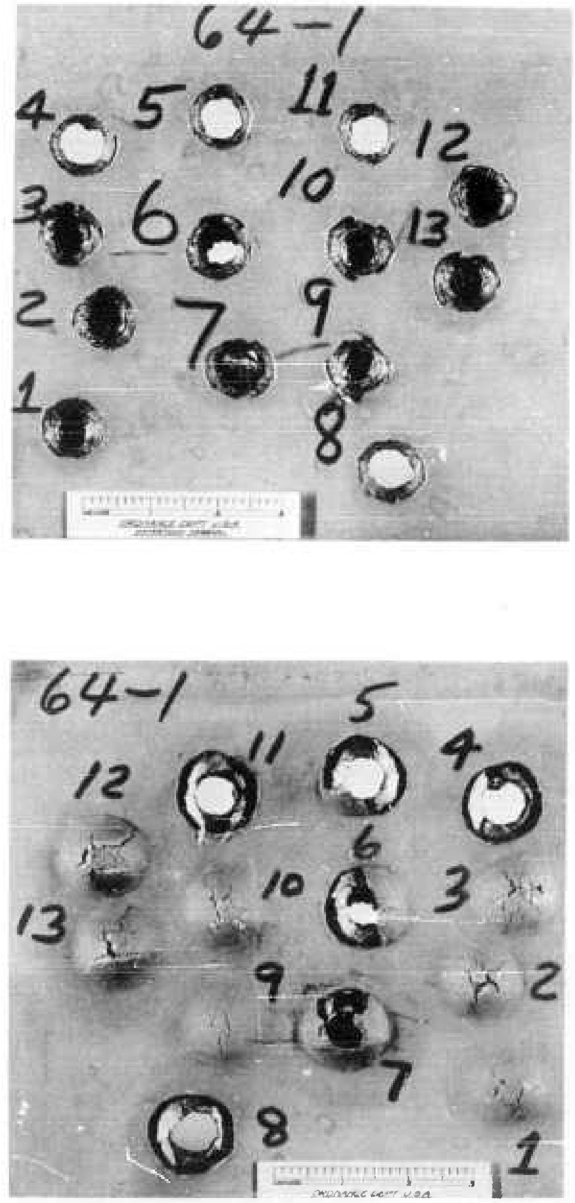

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Figure 6 (U). BALLISTIC TEST PLATE (Ti-6Al-4V ANNEALED, YIELD STRENGTH 125 KSI) AFTER BALLISTIC ATTACK BY CAL. .50 FS PROJECTILE AT 0° OBLIQUITY.(U)

of a carbide at the tip of a delamination crack is presented in Figure 7. This foreign particle was identified as a carbide by anodically oxidizing in a 10 percent NaCN aqueous solution.[8] The alpha and beta turns blue and the carbides appear yellow-orange. There is a definite need for titanium armor with a lower level of carbon. It would be of interest to test ballistically a plate with a carbon level of 0.002 weight percent.

(U) Increased strength has been shown to be beneficial in steel armor for increasing the protection against armor-piercing type ammunition.[9] Ballistic tests have been conducted on the 4Al-4V and 6Al-4V titanium alloys in various heat-treated conditions. No ballistic improvements have been obtained on either alloy, and drastic decreases in the fragment-simulating ballistic performance have been obtained when material is heated above the beta transus.[8]

(U) The mechanical properties of the 4Al-4V alloy are compared in Table II in the annealed and various solution-treated-plus-aged conditions.[6] The 1750 F and 1700 F solution temperatures were above the beta transus and resulted in a transformed beta microstructure and a large grain size. The plates which were beta-solution treated had some strength improvement, but drastically lower elongation and reduction of areas as compared to the annealed plate. Little differences exist in Charpy impact properties at -40 F between the plates heat-treated above the beta transus and the annealed plate. All the plates were tested with both the caliber .30 AP and the caliber .50 FS (207-grain) projectiles. Essentially no differences in the ballistic performance were obtained when the various plates were tested with the caliber .30 AP projectile. However, when ballistically tested with the soft blunt-nose caliber .50 FS projectiles, decreases in protection ballistic limits of 885 and 505 ft/sec were obtained on the plates above the beta transus. The larger decrease in ballistic performance was obtained on the material which was heat treated at the higher temperature.

(U) An explanation for the drastic differences in the fragment-simulating ballistic performance of these plates may be obtained by an examination of the mechanisms of projectile penetrations. Cross sections of two partial penetrations from one of the plates heated above the beta transus and the annealed plate are presented in Figure 8.

(U) The material heated above the beta transus or a plate worked primarily in the beta field fails by a low-energy adiabatic shear process with straight-through plugging. Little or no deformation occurs on the back side of the plate and the punching resistance is near the velocity of the ballistic limit. That is, very little difference in velocity level exists between a partial and a complete penetration.

(U) In the case of the plate with the fine annealed alpha-beta microstructure, an ogive plug forms, internal delamination occur along planes of weakness, and a large amount of plastic deformation occurs on the back side of the plate. At increasing velocity levels, the internal delaminations propagate until a bending moment is built up which overcomes the tensile

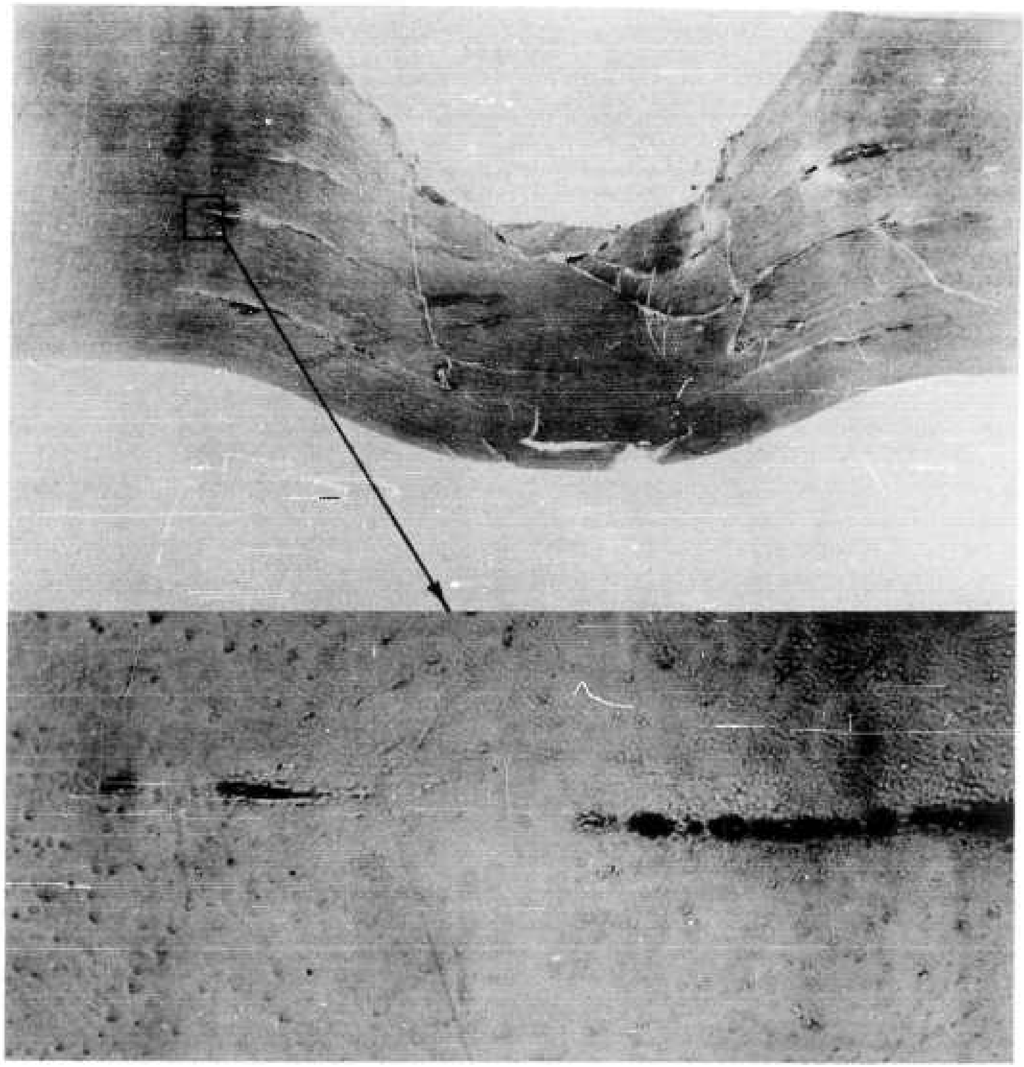

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Figure 7 (U). CARBIDES LINED UP WITH DELAMINATION IN Ti-6Al-4V ARMOR.(U)

TABLE II (U)

Mechanical and Ballistic Properties of Ti-4Al-4V
as Affected by Heat Treatment (U)

Heat Treatment	Yield Strength 0.2% (ksi)	Tensile Strength (ksi)	Elon (%)	R.A. (%)	V-Notch Charpy Impact -40 (ft-lb)	Difference In Protection V_{50} Ballistic Limits 0° Obliquity (fps)
1750 F, 1/2 hr; WQ 1100 F, 1/4 hr; AC	132	141	9.3	27.0	20.5	-885
1700 F, 1/2 hr; WQ 900 F, 1/4 hr; AC	123	138	12.9	32.2	23.3	-505
1650 F, 1/2 hr; AC 1100 F, 1/4 hr; AC	114	116	18.6	49.0	32.2	None
1650 F, 1/2 hr; WQ 1000 F, 1/4 hr; AC	135	143	12.1	38.5	26.5	+105
1300 F, 2 hr; AC	115	116	17.1	54.8	22.3	None

Ballistic Limits Compared with Annealed Ti-6Al-4V, cal. .50 FSP
All Mechanical Properties are transverse

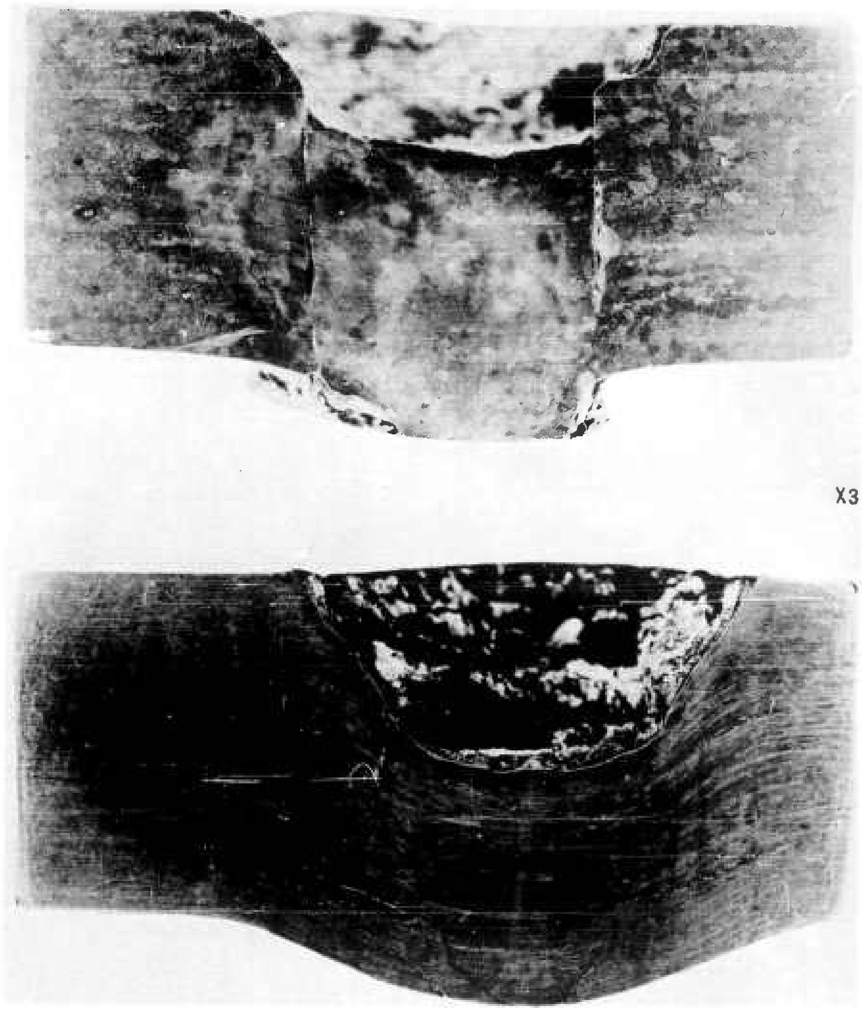

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Figure 8 (U). PROJECTILE PENETRATIONS FROM EMBRITTLED AND UNEMBRITTLED 4Al-4V TITANIUM PLATE.(U)

resistance in the plane of the plate. Complete penetration occurs with the plug and the spall being ejected from the back side of the plate and penetrating the witness plate.

(U) The Charpy V-notch impact test has been used successfully for many years as a microstructure control test in steel armor to insure against undesirable microstructures and to avoid inferior low-temperature shock properties. This test is not adequate to distinguish between the two drastically different microstructures in annealed 6Al-4V titanium armor and, hence, is not being used in the present titanium armor specification. Charpy impact tests were conducted on the annealed and solution-treated (1750 F)-plus-aged plates described in Table II, and these data are presented in Figure 9. Essentially no difference exists in the Charpy impact energy test temperature characteristics of these two plates over the temperature range of -200 C to +200 C.

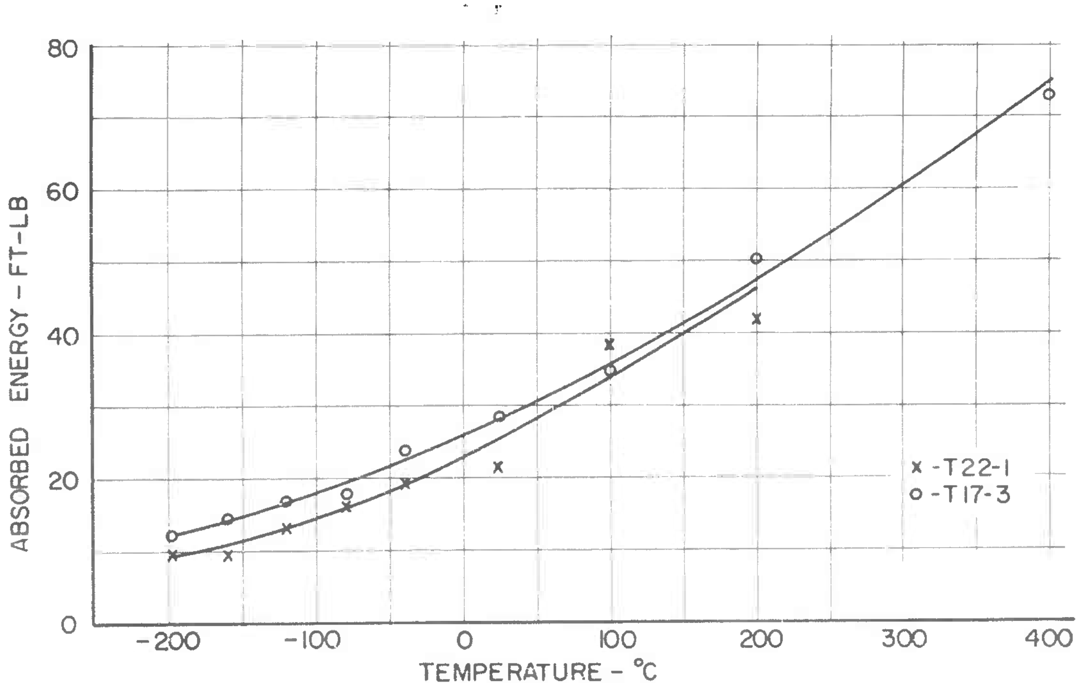
(U) In the early days of the titanium industry, the Charpy impact test was extremely valuable in differentiating between brittle and ductile materials,[1] i.e., those having high and low percentages of interstitial elements. However, now that titanium may be procured based upon close control of chemistry, the Charpy impact test adds little value as a control test for the annealed Ti-6Al-4V armor plate.

(U) The effect of heat treating on the mechanical and ballistic properties of the 6Al-4V titanium alloy are presented in Table III.[7] Although heat treating provides a slight increase in strength level, no major effect on the ballistic performance has been obtained. In addition, heat treating increases the probability of heating above the beta transus which is extremely detrimental for fragment protection.

(U) The present specification[10] and chemical and mechanical properties are presented in Table IV. These specification mechanical properties are aimed at obtaining an extra low interstitial level material in the annealed condition. Three levels of mechanical properties have been specified for the three thickness levels. These have been based upon what the industry can produce and also upon what is needed to meet the ballistic specification requirements.

CURRENT RESEARCH ON TITANIUM ARMOR (U)

(U) Recently,[11] metallurgical and ballistic tests have been conducted on annealed Ti-6Al-4V plate produced by various deformation processing techniques, all from the same ingot. The plate thickness was held constant to minimize the variables. The deformation processing techniques used were straight and cross-rolled material with 1:1 and 2:1 reductions worked both parallel and perpendicular to the ingot axis. In addition, material was pancake forged, upset forged, and a cast plate was cut directly from the ingot. Unfortunately, the rolled plates were heated to 1850 F prior to



HEAT TREATMENT	DIR.	YIELD STRENGTH	ULTIMATE STRENGTH	% ELON.	% R.A.
T22-1 BETA EMBRITTLED					
1750F (1/2 hr.) WQ + 1100F (1/4 hr.) AC	L	124,500 psi	134,000 psi	12.1	30.8
	T	132,000 psi	141,000 psi	9.3	27.0
T17-3 UNEMBRITTLED					
1300F (2 hrs.) AC	L	110,000 psi	112,400 psi	17.1	49.0
	T	115,000 psi	115,600 psi	17.1	54.8

Figure 9. CHARPY V-NOTCH IMPACT TRANSITION CURVE AND MECHANICAL PROPERTIES OF EMBRITTLED AND UNEMBRITTLED 4Al-4V TITANIUM PLATE

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Figure 9 (U). CHARPY V-NOTCH IMPACT TRANSITION CURVE AND MECHANICAL PROPERTIES OF EMRITTLED AND UNEMBRITTLED 4Al-4V TITANIUM PLATE. (U)

TABLE III (U)

Mechanical and Ballistic Properties of Ti-6Al-4V
as Affected by Heat Treatment (U)

Heat Treatment	Yield Strength 0.2% (ksi)	Tensile Strength (ksi)	Elon (%)	R.A. (%)	V-Notch Charpy Impact -40 (ft-lb)
Annealed	125	134.1	15.0	33.3	16.8
1700 F, 1 hr; WQ 1100 F, 4 hr; AC	150	158.4	14.3	36.3	16.8
1400 F, 1 hr; WQ 900 F, 6 hr; AC	130	140.2	15.7	33.1	15.8

No difference in Protection V_{50} Ballistic Limits for either cal .30 AP M2 or cal .50 FS Projectile

All Mechanical Properties are transverse

TABLE IV (U)

Titanium Armor Specification Requirements (U)

Chemical Analysis

Aluminum	5.5/6.5	Carbon	0.04 max
Vanadium	3.5/4.5	Oxygen	0.14 max
Iron	0.025 max	Nitrogen	0.02 max
Hydrogen	0.0125 max		

Minimum Transverse Mechanical Properties

Thickness (inches)	Yield Strength 0.2% Offset (psi)	Tensile Strength (psi)	Elongation (%)	Reduction of Area (%)
1/4 to 1	120,000	130,000	14	30
1 to 1-3/4	115,000	125,000	12	25
over 1-3/4	110,000	120,000	10	20

rolling as compared to the forging temperature of 1750 F. In addition, the forgings received intermediate reheats during the deformation processing cycle.

(U) The tensile ductility (elongation and reduction of area) has been used extensively in titanium specifications. These parameters provide an indication of the degree of processing that the material has received. High elongation and reduction of areas are associated with material which has received a large amount of plastic reduction below the beta transus.

(U) The merit ratings for both the caliber .30 AP and the caliber .50 FSP obtained on the various items are presented in Figures 10 and 11 as a function of tensile elongation and reduction of area. The merit ratings were obtained by dividing the plate ballistic limit by the ballistic limit obtained previously on commercially produced, annealed 6Al-4V rolled plates at the same areal density. A merit rating less than 0.97 or greater than 1.03 is considered a significant change in the ballistic performance for homogeneous materials. The tensile elongation and reduction of area values are an average of four tests on the cast and forged plates and an average of two transverse tests on the rolled plates.

(U) In Figure 10, the tensile elongation obtained on the various items is presented as a function of the merit rating for both the caliber .50 FS projectile and the caliber .30 AP ammunition. The merit ratings obtained with the caliber .50 FSP vary from a low value of 0.80 for the cast titanium plate to a high of 1.08 for the cross-rolled material worked perpendicular to the ingot axis. The two forged products had merit ratings of 1.04 and 1.07 for the pancake forging and upset forging respectively.

(U) When the various plates were tested with the caliber .30 AP projectile, a low merit rating of 0.98 and a high value of 1.11 were obtained on the cast and the upset-forged plates respectively. As indicated in Figures 10 and 11, both improved armor-piercing and fragment-simulating ballistic performance is associated with high tensile ductility. It is interesting to note in these two figures that all the plates passed the minimum proposed specification ballistic performance, even the cast plate, when tested with the hard, sharp-nose armor-piercing projectile. However, in the case of fragments, which is important for protection up to an armor thickness of one inch, the ballistic performance is dependent upon the tensile ductility, which is a function of the amount of plastic working and the hot-working temperature. These factors are also evident in the resultant plate microstructure.

(U) Examples of plate microstructures with increasing desirability for armor are presented in Figures 12, 13, and 14. The photomicrograph presented in Figure 12A was obtained on the cast plate which had a merit rating of 0.80 when tested with the caliber .50 FS projectile. This plate has a large prior beta grain size with a transformed microstructure (Widmanstatten alpha). Plate B in Figure 12 has received very little deformation below the beta transus and is also extremely undesirable for fragment-resistant armor. Plates C and D presented in Figure 13 are still

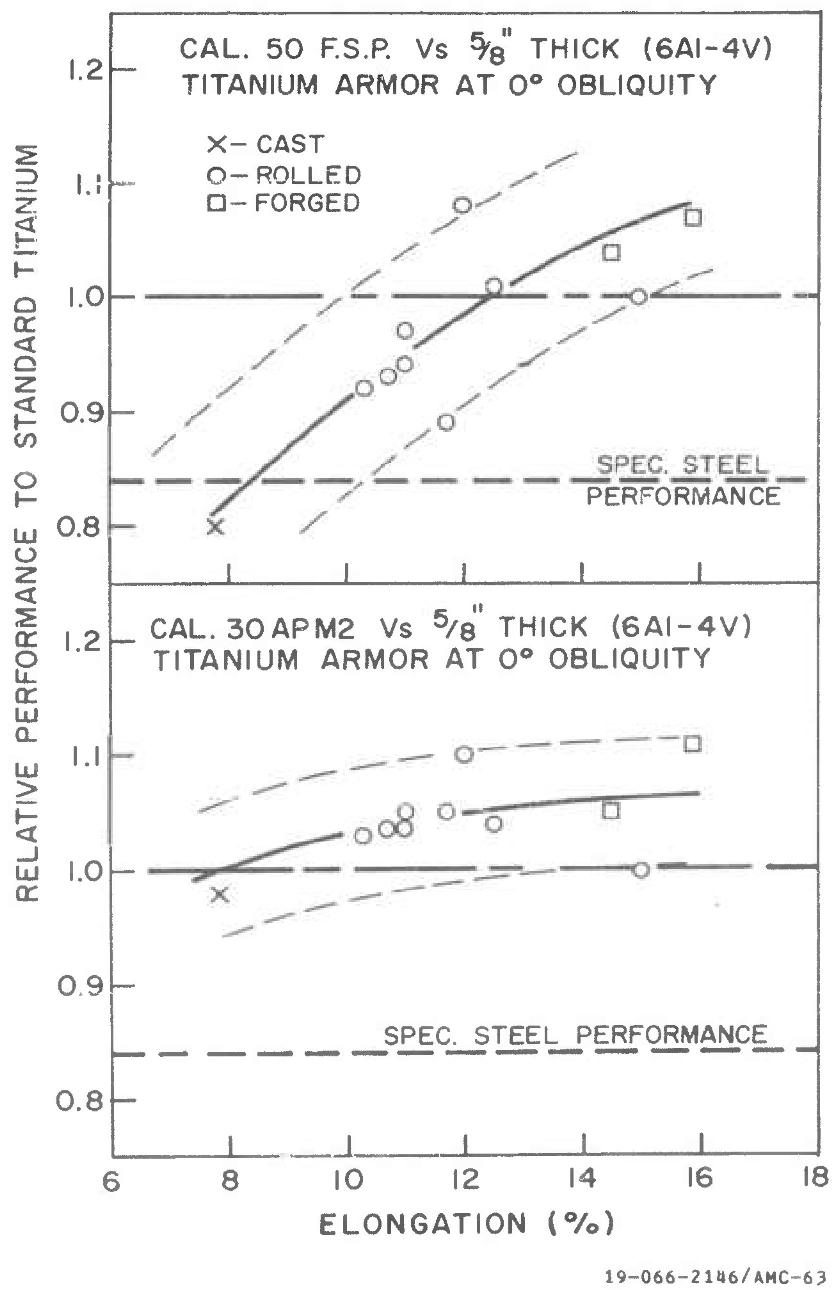


Figure 10 (U). EFFECT OF TRANSVERSE ELONGATION ON BALLISTIC PERFORMANCE. (U)

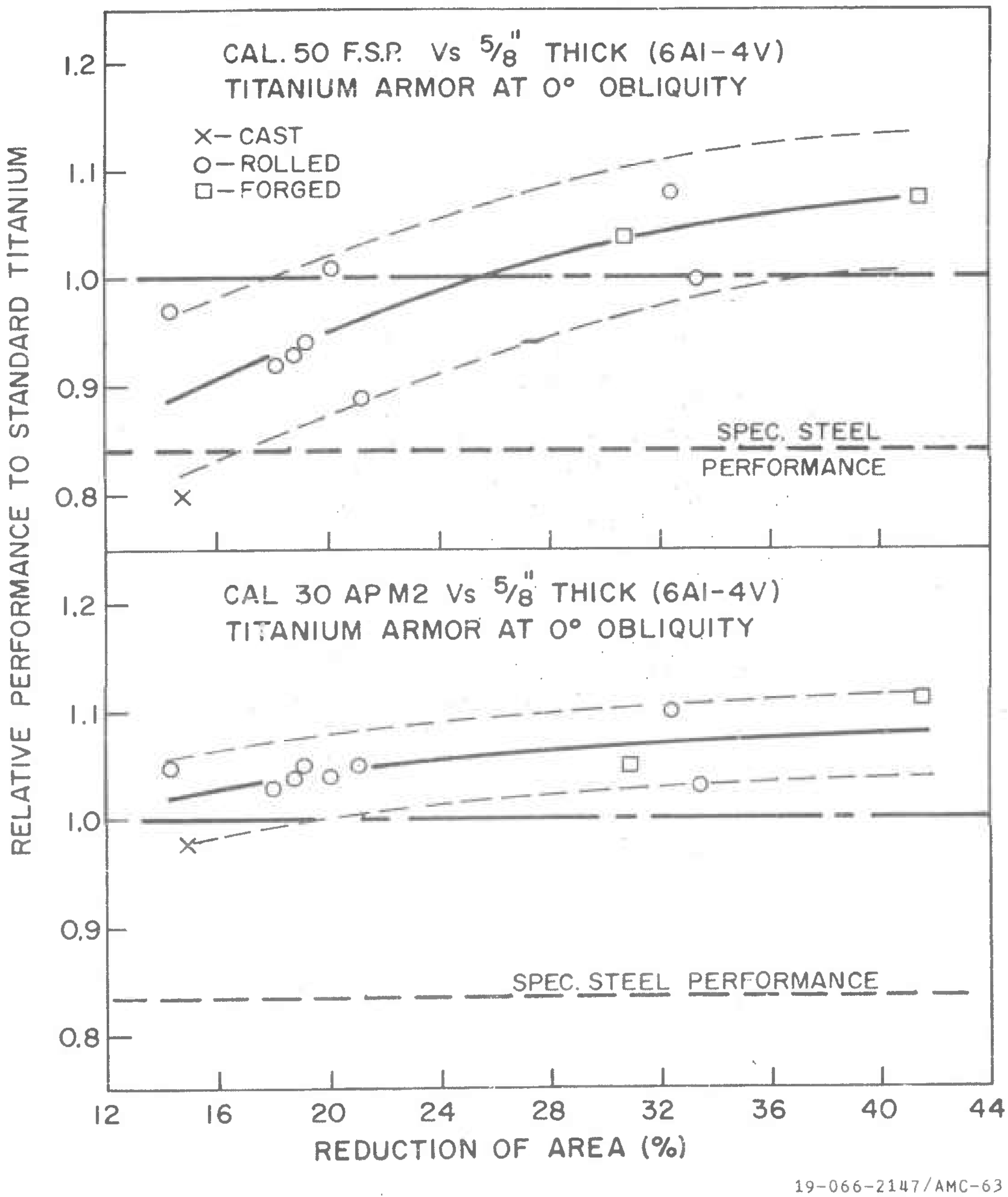
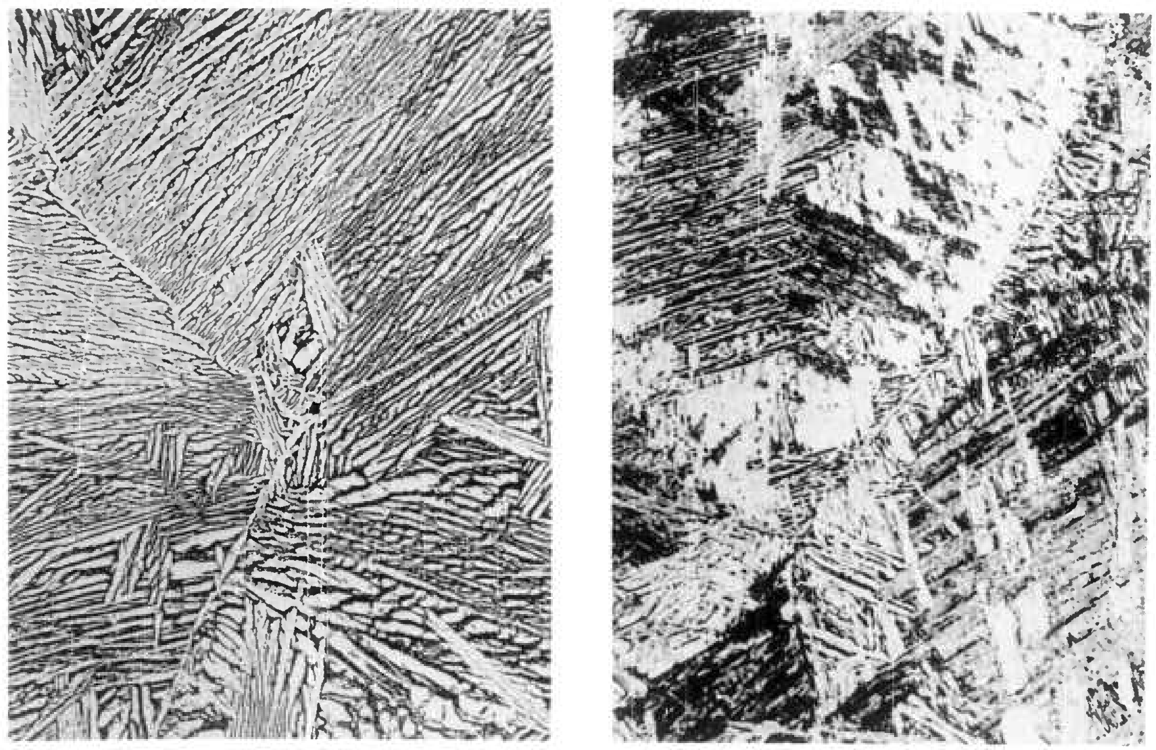


Figure 11 (U). EFFECT OF TRANSVERSE REDUCTION OF AREA ON BALLISTIC PERFORMANCE.(U)



A

CAST

Yield Strength	116 ksi
Ultimate Tensile Strength	123 ksi
Elongation	7.8%
Reduction of Area	14.7%

B

ROLLED PLATE

Yield Strength	121 ksi
Ultimate Tensile Strength	136 ksi
Elongation	11.4%
Reduction of Area	23.6%

X500

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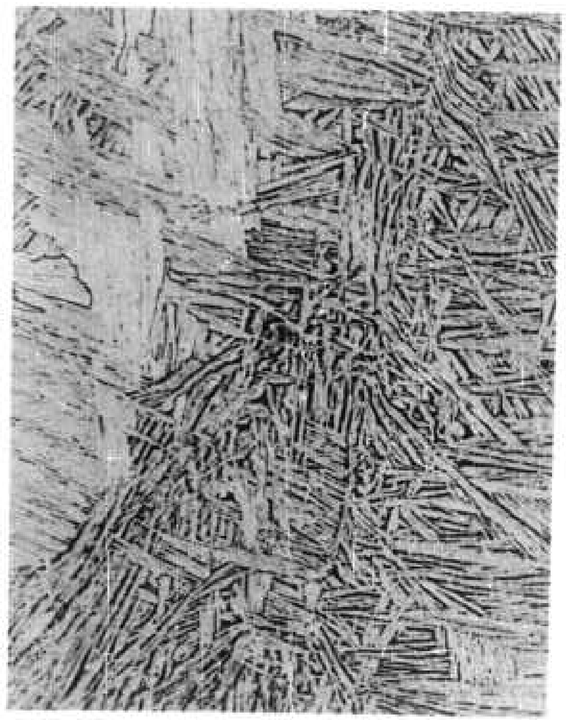
Figure 12 (U). TITANIUM ALLOY (6Al-4V) MICROSTRUCTURES.(U)



C

ROLLED PLATE

Yield Strength	124 ksi
Ultimate Tensile Strength	144 ksi
Elongation	12.5%
Reduction of Area	23.5%

D

ROLLED PLATE

Yield Strength	129 ksi
Ultimate Tensile Strength	143 ksi
Elongation	13.0%
Reduction of Area	31.5%

X500

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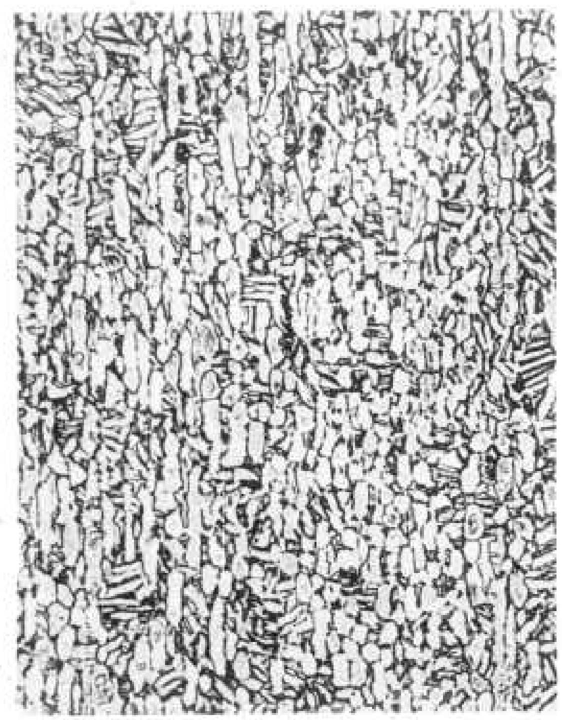
Figure 13 (U). TITANIUM ALLOY (6A1-4V) MICROSTRUCTURES. (U)

E

ROLLED PLATE

Yield Strength	115 ksi
Ultimate Tensile Strength	120 ksi
Elongation	15.0%
Reduction of Area	33.0%



F

FORGED PLATE

Yield Strength	130 ksi
Ultimate Tensile Strength	135 ksi
Elongation	14.5%
Reduction of Area	35.9%

X500

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Figure 14 (U). TITANIUM ALLOY (6Al-4V) MICROSTRUCTURES. (U)

undesirable for armor and contain partially broken-up acicular microstructures. Plates E and F are desirable for armor, with plate F being the better of the two, and possess a finer broken-up alpha plus beta microstructure. This plate had a merit rating of 1.07 when tested with the caliber .50 FS projectile and 1.11 when tested with the caliber .30 AP projectile.

(U) The forgings tested during the recent armor study described briefly above exhibited higher ballistic performance against both the armor-piercing and fragment-type ammunition than that exhibited previously by titanium armor. However, this should not be the upper limit in ballistic performance since one obvious deficiency still exists, namely, back-spalling. Examples of back-spalling in good-quality annealed 6Al-4V armor have been presented in Figures 2 and 6 for plates tested with large-diameter AP and caliber .50 FS projectiles. The discontinuities which are responsible for the spalling are not of the nonmetallic type attributed to spalling in steel armor since titanium is a double-consumable-electrode vacuum-melted product.[12] Therefore, these discontinuities must be associated with variations in the phase and/or alloy distribution.

(U) An example of the heavy 2-inch-thick 6Al-4V plate tested at APG which spalled under 76MM AP projectile attack without the projectiles penetrating the plate is presented in Figure 15. As indicated before, back-spalling under AP projectile attack without the projectile penetrating the test plate results in low ballistic performance. This plate and the other heavy plates were evaluated metallurgically at AMRA. The 2-inch-thick armor plate was found to be the inferior plate in the group and was heavily banded as evidenced by the through-thickness macro section presented in Figure 16. A micro hardness survey (500-gram load) was conducted across a typical band and these data are also presented in Figure 16. The two sets of data in this figure are for the different orientations of the indentor. Very little difference existed due to indentor orientation. The hardness values converted to Rockwell C vary from 21 to 39. As indicated by Professor Flemings,[14] the peaks and valleys, that is, the maximum and minimum values, do not change under further plastic deformation; only the distances between them change. It is believed that further plastic deformation below the beta transus in the case of this 2-inch armor would have refined the microstructure but would not have eliminated the banding and therefore the hardness differences. Micro hardness surveys using 25-gram loads have also been conducted on good quality 1-inch-thick armor, and variations from 88 Rockwell B to 44 Rockwell C have been obtained.

(U) The mechanical properties obtained from the three major plate directions on the 2"-, 3"- and 5"-thick-plates are presented in Table V. The tensile elongation and reduction of area values on the 2-inch plate are generally lower than the 3- and 5-inch plates. In addition, the short transverse properties on the 2-inch plate are significantly lower than the longitudinal and transverse properties from the same plate. Additional information is needed on the effects of deformation processing on the short transverse properties and methods for obtaining improvements. These properties are not only dependent upon banding, but also upon crystallographic textures. In future years materials having controlled crystallographic textures may be used to obtain ballistic improvements.

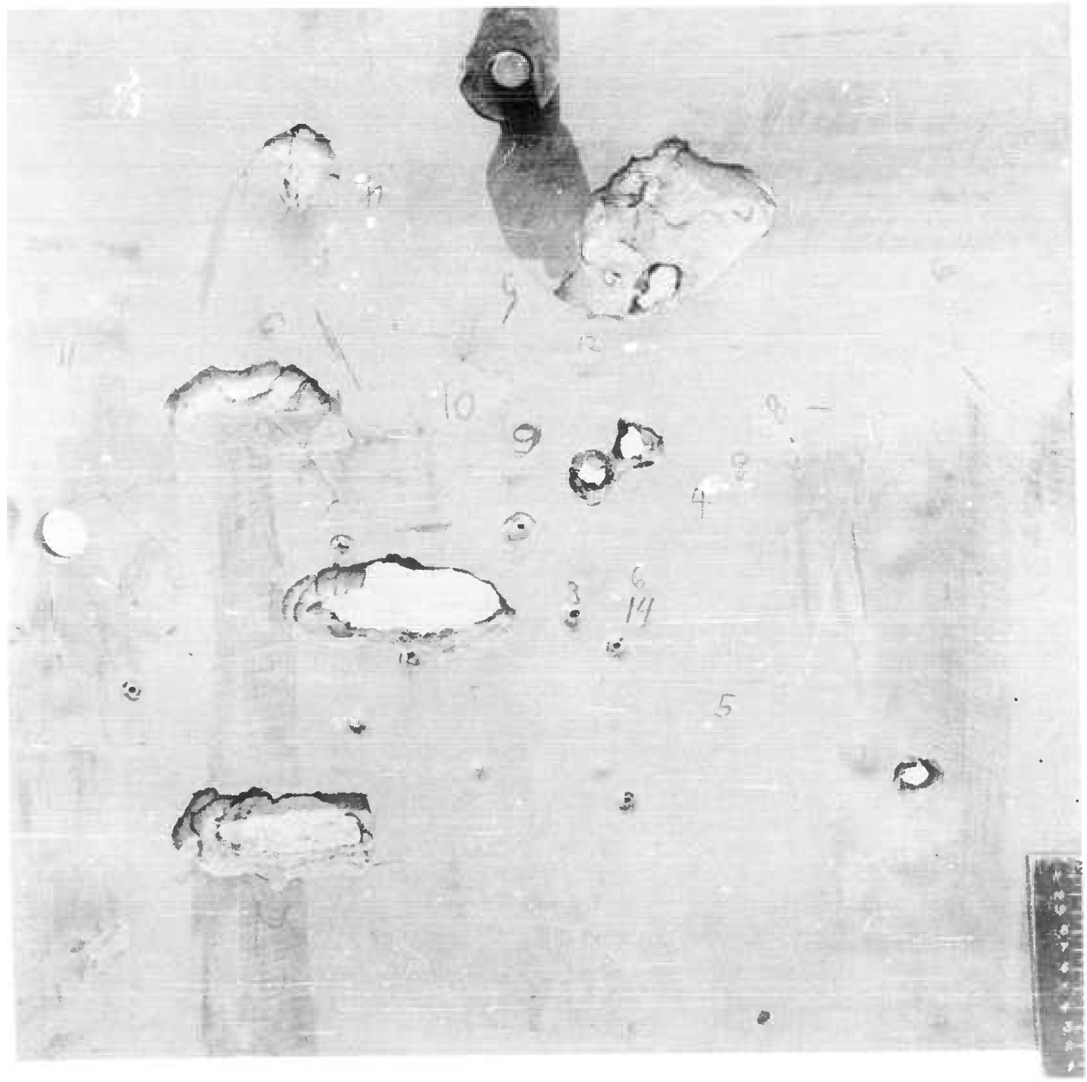

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Figure 15 (U). LARGE BACK SPALL IN 2-INCH-THICK Ti-6Al-4V ARMOR AFTER BALLISTIC ATTACK BY 76MM PROJECTILE.(U)

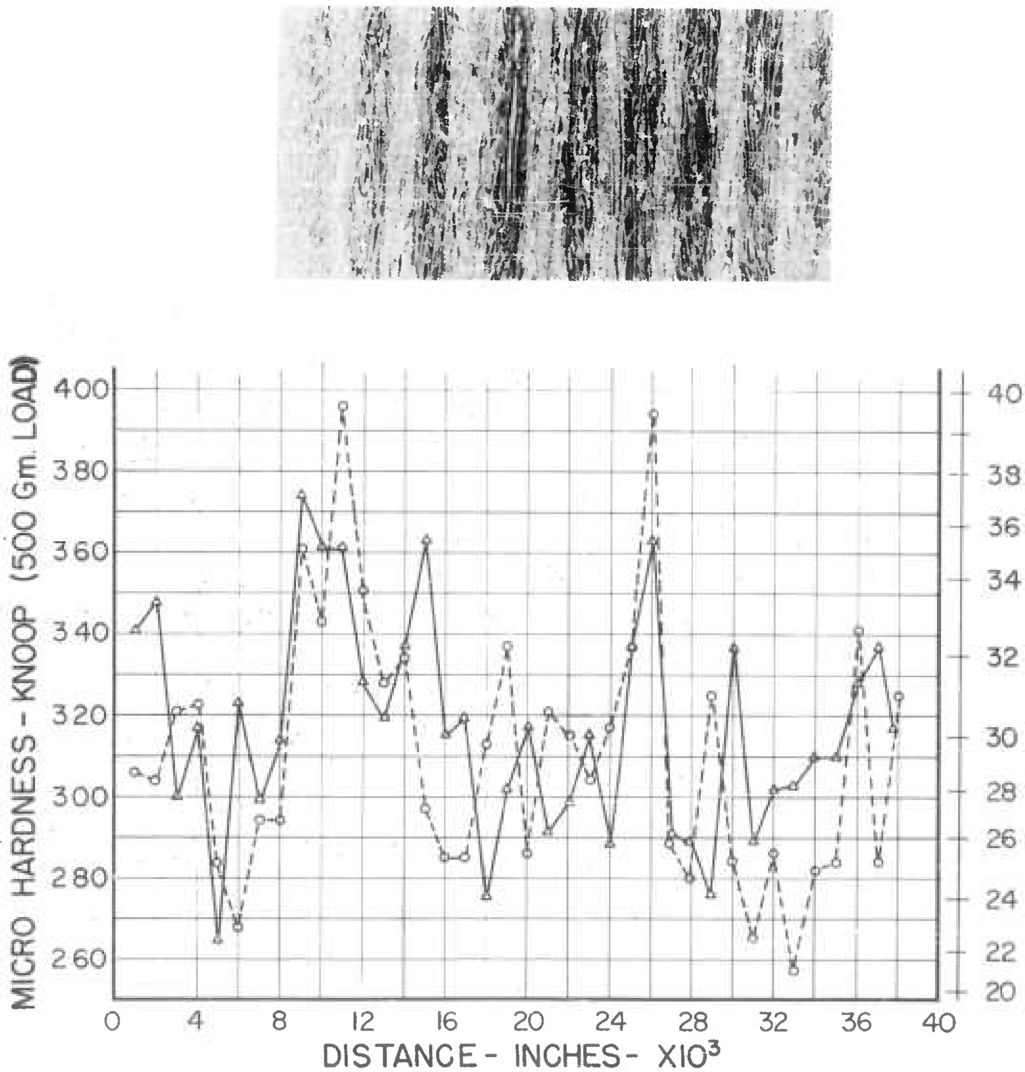

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Figure 16 (U). MICROHARDNESS SURVEY ACROSS HEAVILY BANDED 2-INCH Ti-6Al-4V ARMOR PLATE. (U)

TABLE V (U)

Mechanical Properties of 2", 3" and 5" Thick
Titanium (6Al-4V) Armor (U)

Direction of Specimen	Y.S. 0.2% (ksi)	UTS (ksi)	Elon (%)	R.A. (%)	Energy Absorbed (ft-lb-40°)
		2-Inch Section			
1	118.3	137.4	11.4	20.1	16.5
2	122.5	140.5	12.2	23.4	15.2
3	114.7	127.5	7.9	15.2	11.5
		3-Inch Section			
1	114.5	125.0	13.0	27.8	17.8
2	113.0	125.0	13.5	25.4	17.1
3	108.7	120.4	12.0	31.4	15.5
		5-Inch Section			
1	116.0	125.0	14.5	30.1	21.1
2	116.5	122.8	13.5	28.6	15.8
3	113.6	127.7	12.0	18.9	11.0

Directions 1 and 2 are arbitrary longitudinal and transverse directions.

Direction 3 is the short transverse direction.

All values are the average of 2 or more tests.

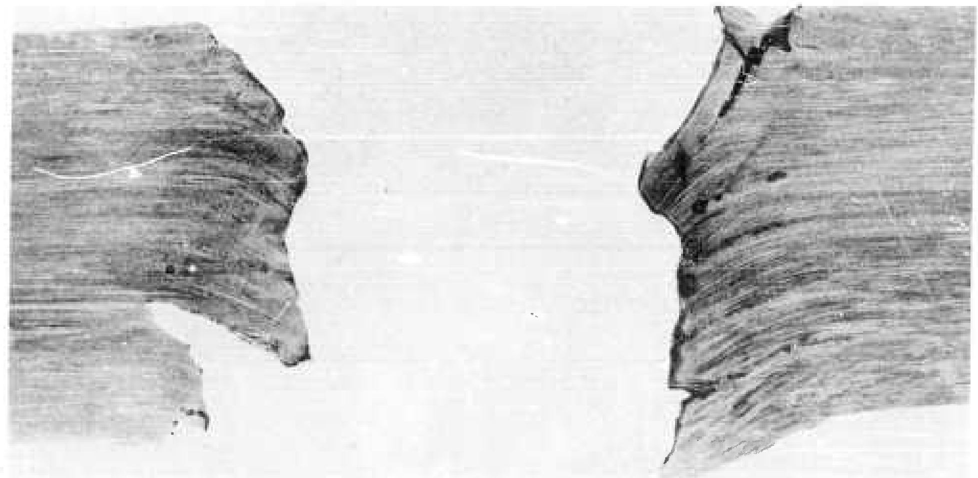
(U) An example of hardness variation in good quality 5/8" 6Al-4V armor is presented in Figure 17. Micro hardness readings were obtained across the end of a delamination crack in a plate which was tested with the caliber .50 FS projectile. These hardness readings have essentially the same variation as the 2-inch armor (22 to 37 Rockwell C). The cracking is directly associated with the hard phase. Electron beam micro analyses have been conducted across two of the delamination cracks presented in the figure. The cracking was found to be associated with a band poor in the second phase.[15] That is, the band was high in aluminum and poor in vanadium and iron (7Al, 3V and 0Fe).

(U) Some limited ballistic and metallurgical tests have also been conducted on the high-strength, 190 ksi ultimate strength, 6Al-6V-2.5Sn titanium alloy rolled plate. When tested with the caliber .50 FS projectile, a merit rating of 0.80 was obtained with all complete penetrations associated with the ejection of large back spalls from the rear of the test plate; on the fifth round, the plate fractured. The rear surface of the plate is presented in Figure 18 and a view of the fractured surface is presented in Figure 19. A cross section of the penetration that resulted in plate fracture with photomicrographs of a banded area that transversed the sample are presented in Figure 20. Photomicrographs of the band indicated a transformed microstructure with a large beta grain size. The high magnification photomicrograph indicates a carbide found within the banded area which is typical of that shown previously in the 6Al-4V alloy. The base metal microstructure is typical of a properly worked and heat-treated highly stabilized alpha and beta alloy. An electron beam microprobe analysis traverse was conducted across the banded area. A comparison of the average analysis of the matrix and the band are presented below:

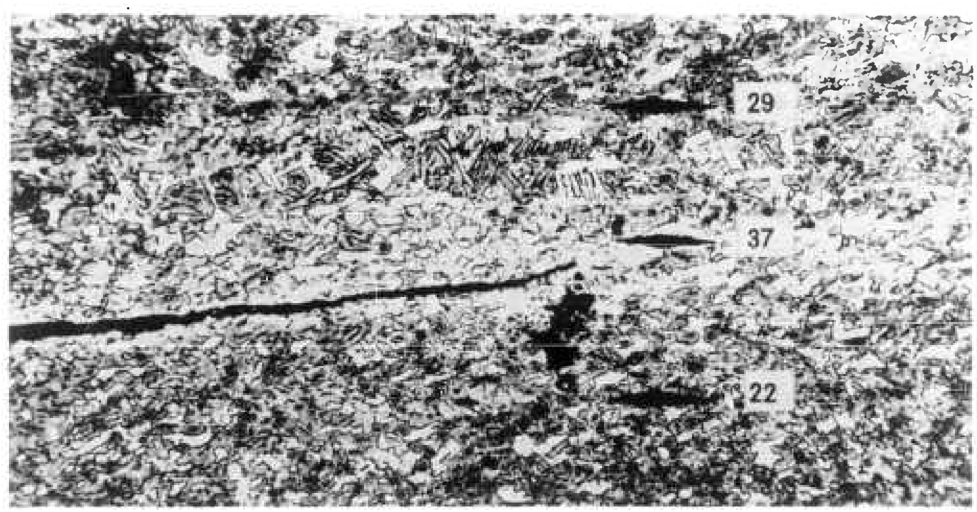
Alloy	Base Metal	Band
	weight	(percent)
Aluminum	5.5	5.5
Vanadium	5.5	5.8
Iron	0.77	1.20
Tin	1.84	1.55
Copper	0.80	1.50

All these chemistry changes tend to decrease the beta transus. Thus, if the plate was being worked close to the base metal transus, then the material in the band would be heated above its transus. This would explain the large differences in microstructure. In addition to analyzing the chemistry of the band, the foreign particle within the band was examined. It was determined to be a titanium-base carbide.

(U) Mr. Abbott has indicated the ballistic advantage to be gained by the ultra-high-strength steel. This may also follow through for titanium armor; however, it appears that we are at the intermediate stage on the



CALIBER .50 FSP PENETRATION X8



MICROHARDNESS (100-GRAM LOAD) SURVEY AT THE END OF A SPALL CRACK X100

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Figure 17 (U). BALLISTIC TEST PLATE 5A Ti-6Al-4V ALLOY (R-ETCH).(U)

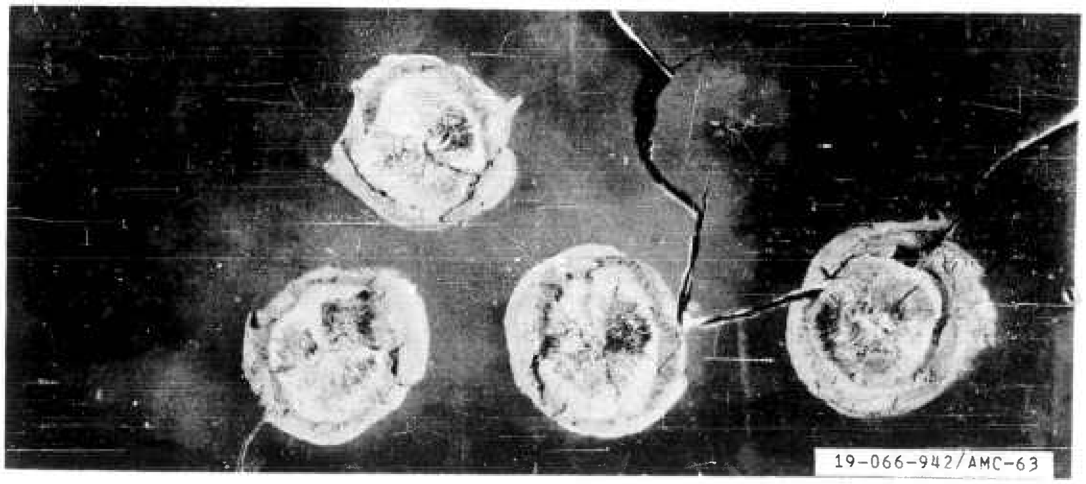

Figure 18 (U). TITANIUM ALLOY (6Al-6V-2.5Sn 1625 F WQ + 1150 F 4 HOURS) AFTER BALLISTIC ATTACK BY CAL. .50 FS PROJECTILE AT 0° OBLIQUITY. (U)

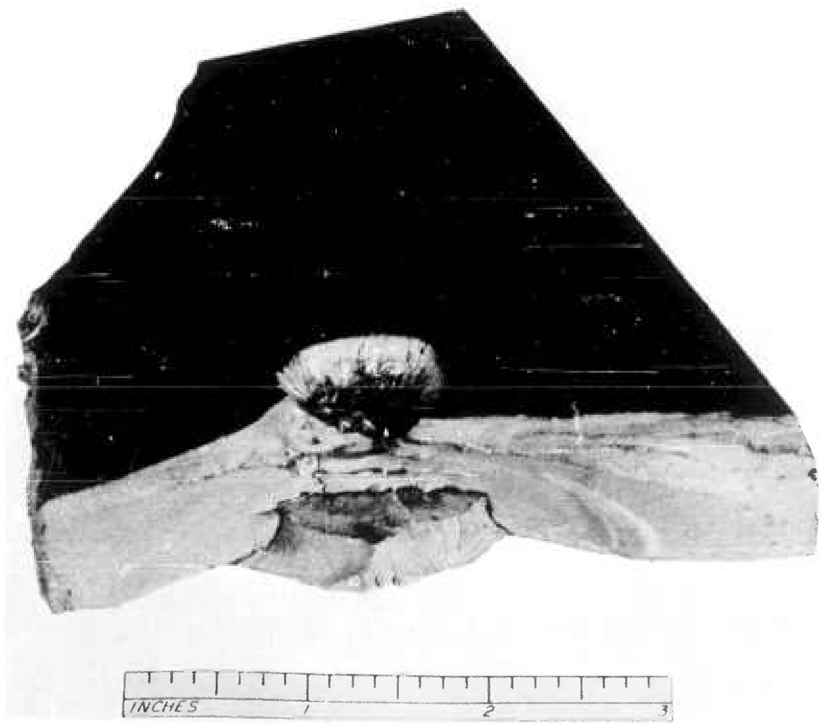

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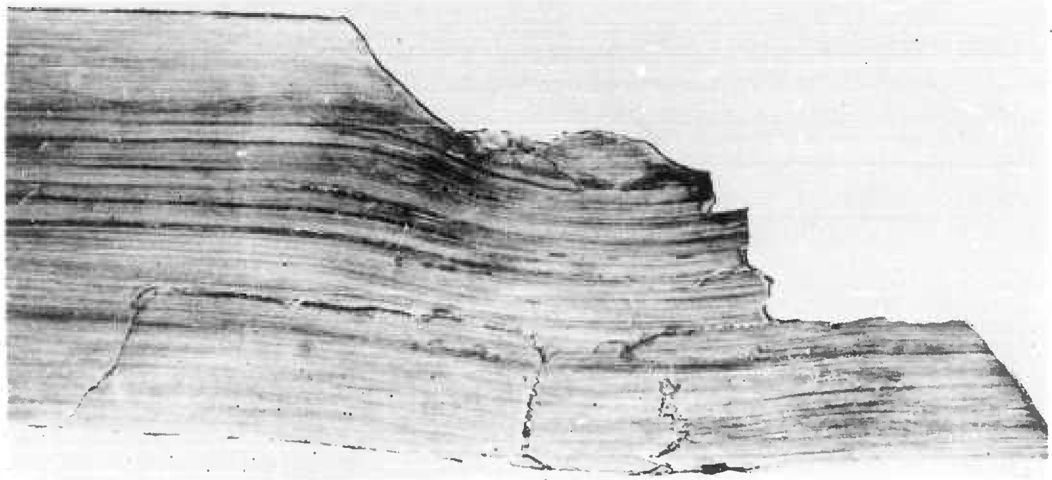
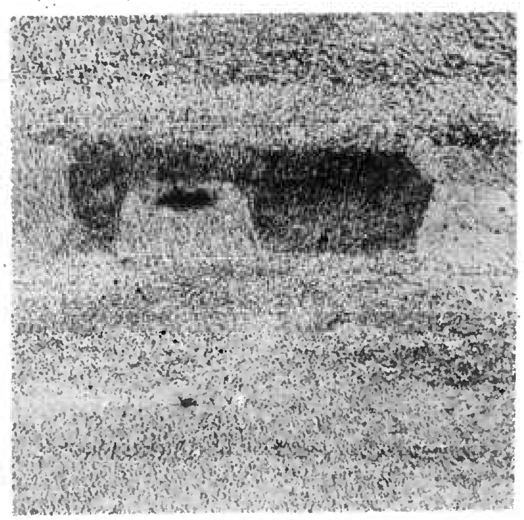
Figure 19 (U). FRACTURE SURFACE ON HIGH STRENGTH TITANIUM 6Al-6V-2.5Sn ROLLED PLATE. (U)



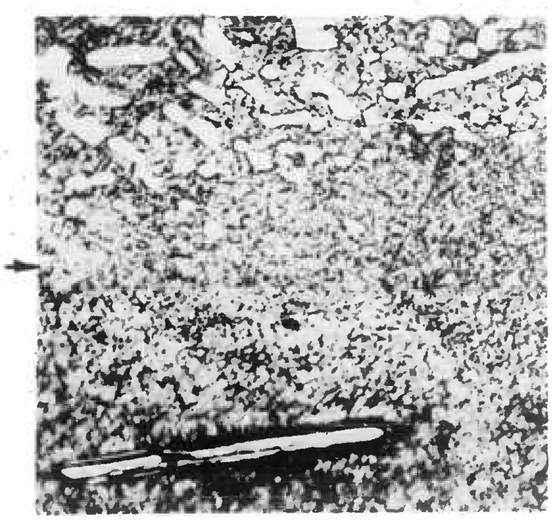
X3

FRACTURE IN TITANIUM PLATE UNDER BALLISTIC IMPACT



X100

ALLOY BAND IN TITANIUM PLATE



X1000

CARBIDE IN ALLOY BAND

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Figure 20 (U). BANDED HIGH STRENGTH TITANIUM 6Al-6V-2.5Sn PLATE (R-ETCH). (U)

hardness curves where brittle failures in the plate rather than of the AP projectiles occur and result in decreased ballistic performance. This decreased ballistic performance has been obtained on the highly stabilized alpha and beta alloy (Ti-13V-11Cr-3Al) at 190 ksi ultimate tensile strength levels. It would be of academic interest to test titanium at the higher strength levels (greater than 200 ksi). However, such a product could not be envisioned for use as the major construction material for armored vehicles because of the insurmountable fabrication problems (welding) and environmental problems (low-temperature brittleness). These same problems exist for the ultra-high-strength steels and ceramics.

(U) Because of its superior ballistic characteristics against a variety of projectiles and attack conditions, a major effort in the rolled armor field should be directed to improving the 6Al-4V alloy. Additional research is needed in two directions. The first of these is basic solidification research to eliminate or minimize the ingot inhomogeneities which, when rolled into ballistic test plates, are planes of weakness in the thickness direction and are associated with spalling during ballistic impacts. The other area of major importance is to develop improved deformation processing procedures and mechanical and metallurgical data for use in titanium armor specifications for controlling and improving production material. In addition, fabricability of the 6Al-4V alloy armor plates into the shapes needed for vehicles, must be considered. Information gained through basic solidification research on the 6Al-4V titanium alloy would also be applicable to the high-strength titanium alloys. Once the planes of weakness which are resulting in brittle plate failures are eliminated, then higher strength titanium alloys may be used to obtain ballistic improvements.

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